Permanent-magnetic Synchronous Frequency-convertible Centrifugal Compressor and Heat Pump System

Hua Liu[a], Bin Hu[b,*], R.Z. Wang[b], Zhang Zhiping[a], Li Hongbo[a], Wang Sheng[a]

[a]*GREE Electric Appliances, INC. Zhuhai 519070, China*
[b]*Institute of Refrigeration and Cryogenics, Shanghai Jiao Tong University, Shanghai 200240, China*

Abstract

Permanent-magnetic Synchronous Frequency-convertible (PSF) compressor as a new technology has been widely used in heating, ventilation and air conditioning. For centrifugal compressor, some key technologies of large working range 3-Dimentional impeller, 360° circular refrigerant injection port, two-stage impeller directly driven by PSF motor and high-speed inverter are adopted to improve the compressor efficiency. The detail information of these technologies is introduced to show the advantage of efficiency improvement. Experimental results show that the adiabatic efficiency of PSF compressor is 78.1%~87.6%, which is much higher than the conventional frequency-convertible centrifugal compressor. The mechanical efficiency and motor efficiency of PSF compressor are 97%~98.8% and 95%~97.6%, respectively. To further evaluate the system performance of PSF centrifugal heat pump system, a district heating project with waste heat recovery from industry was conducted in Lijingwan community, Shijiazhuang City, Hebei Province. Filed testing results have shown that the heating COP of 500 RT centrifugal heat pump units is up to 6.2 with the water outlet temperature of 10℃ in evaporator side under full load condition.

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Keywords: Permanent magnet synchronous, Frequency-convertible, Centrifugal compressor, Heat pump, District heating.

1. Introduction

With the development of urbanization, the urban construction area of the north of China is expected to reach 15 billion square meters of 2020 [1]. The building heating supply demand will further increase. As a result, the construction heating in northern China has a significant potential in building energy-saving field because of the high energy consumption and correspondingly huge market. At the same time, along with rapid growth of energy demand for construction heating, the traditional heating supply method of coal-fired boiler has brought serious pollution problems. For example, the most area of the north of China suffers from heavy haze in winter. Studies [2] have shown that PM2.5 is the main pollution composition of severe haze weather and reduction of NO_x emissions is the key to control PM2.5. However the main source of NO_x is the burning of fossil fuels (including coal and natural gas). Based on the analysis of pollutant emission sources of haze pollution in Beijing, the emissions of coal-fired heating contribute 18.7% of total pollutants [3]. Wang Y [4] pointed out that the main reason for the haze in northeast China is the exhaust gas of coal-fried and gas-fired boiler from city resident and surrounding houses. In 2013, “Action Plan of Air Pollution Prevention and Control” was issued by the State Council of China. According to the requirements, it is more urgent to develop district heating and alternative clean energy and small industrial coal-fired boilers will be fully eliminated [5]. Therefore, seeking more efficient and cleaner heating energy, fully replacing the traditional boiler heating method and achieving the goal of energy saving, emission reduction and environment protection have great significance for sustainable and stable development.

Among all the existing heating sources, coal-fired and gas-fired boilers account for a very large proportion. The heating area of coal-fired boilers and gas-fired boilers are 4 billion and 0.5 billion square meters respectively [6]. From the perspective of thermodynamics, combustion temperature of the coal-fired and gas-fired boiler is higher than 1000°C, then after exchanging heat with several processes, the hot water supplied for building heating is about 100°C or less. The energy and exergy loss is larger than most of the heating method [7]. While, large amounts of low grade heat can be used to justify the requirements of heating and living for useful purposes. Utilizing more efficiency technologies could provide considerable energy saving in urban heating and reduce the global CO_2 emission by upgrading low temperature heat to higher temperatures.

Fang *et al.* [8] conducted an absorption heat pump district heating project in northern China with 122 MW waste heats recovered from a cement plant and a copper smelter. The case analysis showed the thermal energy efficiency of the cement plant increased from 62.9% to 74.3%, and that of the copper plant increased from 30.1% to 74.7% in heating seasons. R. Lazzarin and M. Noro [9] analyzed the economic performance of gas derived heat pump for district heating during three years of operation. The results demonstrated that current plant layout (heat pump coupled with internal combustion engine) has better energy efficiency than the cogeneration system in district heating, among other efficient heating technologies nowadays. Carli *et al.* [10] presented the energetic and economic aspects of a district heating and cooling based on a closed-loop ground source heat pump, including the density of population in the district where the buildings are located. Economic analysis and payback times are investigated as a function of inhabitant density, adopted solutions, as well as different economic benefit scenarios. The conclusions indicted that primary energy consumption may be reduced in a range of 50-80% compared to traditional systems. Haiwen *et al.*[11] conducted a field measurement on the energy efficiency of an actual seawater source heat pump system for district heating. The results showed that there is about an average of 24.2% energy efficiency enhancement potential of the heat pump units in the project. Lund and Persson [12] investigated the potential heat sources of heat pumps for district heating in Denmark. The analysis showed that low-temperature industrial excess heat is the potential heat sources at present and that sea water will play a substantial role as a heat source in future energy systems mostly.

As for the PSF centrifugal compressor and heat pump district heating system, the reference sources are quite limited. Taegen, F *et al.* [13] briefly described the noise and vibrations problems of permanent-magnet synchronous compressor. Two specific motors were used to illustrate the production mechanism of the noise and vibrations as well as to reduce noise and vibrations. Chen J [14] presented the vector control mothed for permanent magnet synchronous motors. By decomposing a stator current into a magnetic field-generating part and a torque-generating part, both components can be controlled separately and realize smooth rotation over the entire speed range of the motor, full torque control at zero speed, and fast acceleration and deceleration. Wu and Xu [15] analysed various kind of energy losses based on the mechanism of centrifugal compressor. It showed that the incident and separate loss play the most important roles for the compressor operation efficiency under different adjusting approach.

At present, centrifugal heat pumps adopt frequency-convertible technology to improve the energy efficiency and system performance. However, the triple-phase asynchronous motor with an external frequency converter is widely used in traditional centrifugal heat pump to regulate impeller speed. The maximum speed of triple-phase asynchronous motor is less than 3000 rpm, so it is necessary to use speed-increasing gear to drive the impeller to a relatively high speed. Due to the large mechanical losses (up to 8% of the total power consumption) and low motor efficiency (less than 95%), the system performance of centrifugal heat pump is limited. Although there are some investigations on centrifugal compressors and heat pump systems, it is still lack of large capacity centrifugal heat pump system with Permanent-magnetic Synchronous Frequency-convertible (PSF). The compressor efficiency and system performance for centrifugal heat pump can be further improved. In this paper, the key technology information of large working range 3-Dimentional impeller, centrifugal diffuser with low consistency, 360° circular refrigerant injection port and two-stage impeller directly driven by PSF motor are introduced. Based on the new developed PSF centrifugal compressor, a PSF centrifugal heat pump system for district heating project was conducted to investigate the compressor efficiency and system performance. PSF centrifugal heat pump with low grade heat recovery for district heating can greatly reduce the local pollutant emission and increase the thermal efficiency of primary energy.

2. PSF centrifugal compressor

Compressor is the key component for refrigeration and heat pump system. The traditional centrifugal compressor is designed and manufactured according to the full-load operating condition. When the centrifugal compressor is operated in part-load condition, the cooling/heating capacity proportional reduced with the compressor speed decrease. While the pressure head of centrifugal compressor decreased quadratically with the reduction of compressor speed, which may lead to the heat pump surge or unstable working problems. In practical operation, the control strategy of variable speed compressor and adjustable guide glade are used for traditional centrifugal compressor. When the part-load is below 50%, the guide glade must turn down to prevent the surge occurred. In this case, small guide glade produces big throttling loss, leading to the decline of compressor adiabatic efficiency. Therefore, the centrifugal compressor design method based on the full-load operating point is unable to prevent the great reduction of adiabatic efficiency in the part-load condition; no matter it is constant frequency or variable frequency compressor. To achieve high adiabatic efficiency in the whole operating range, a new design method is applied for PSF centrifugal compressor.

The PSF centrifugal compressor is designed according to 75% part-load condition, and then expanded to 50% part-load condition and the full-load operating condition. With this compressor design method, the heating capacity can be regulate just by changing the compressor speed. Only when the part-load is below 25%， the guide glade is used to adjust the heating capacity. This compressor design method reduces the throttling loss caused by the guide glade, and improves the adiabatic efficiency of the compressor.

In order to further improve the compressor efficiency, several special designs are also conducted. Such as large working range 3-Dimentional impeller, 360° circular refrigerant injection port, two-stage impeller directly driven by PSF motor, high-speed PSF motor and inverter. The adiabatic efficiency, mechanical efficiency, motor efficiency and inverter efficiency have been improved obviously. The improved centrifugal heat pump is introduced as follow.

2.1. Large working range 3-Dimentional impeller

The traditional 2-Dimentional impeller is made of cylindrical surface with bended. The meridional channel is narrow, and the processing is not difficulty. The 3-Dimentional impeller is made of space surface with bended and rotated. The width of meridional channel is large, which has the characteristics of high efficiency, smooth curves, large working range and difficult processing. By optimizing the in internal impeller profile, the impeller surface is fully consistent with gas streamline of the flow field, it is easy to suppress the blade vortex flow and improve the internal flow field of the impeller, which effectively reduces the impeller import and export losses (Figure 1, 2). The impeller performance under different operating conditions is effectively ensured.

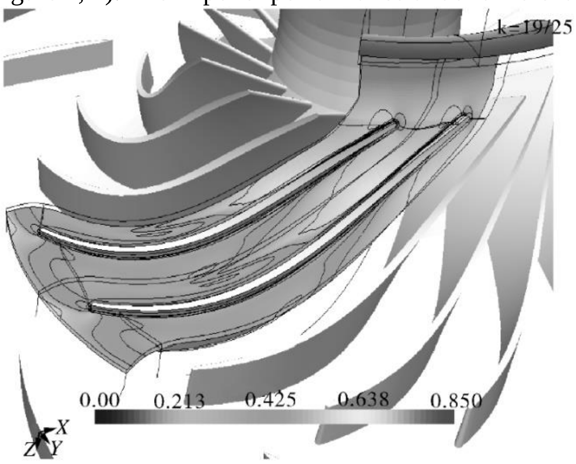


Fig.1 Flow field of internal impeller

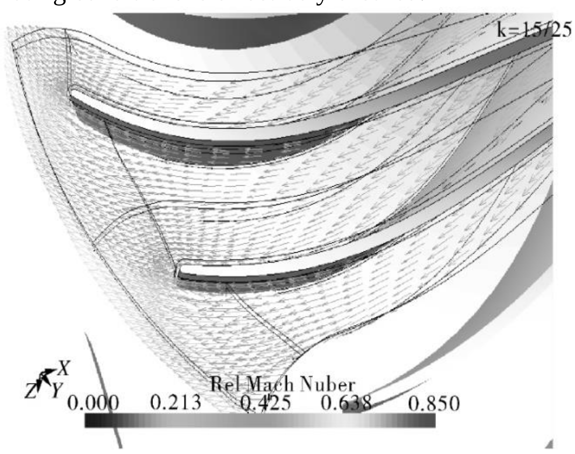


Fig.2 Flow field of impeller outlet

2.2. 360° circular refrigerant injection port

The refrigerant injection port is designed as circular convergence structure, which is arranged near the exit of backflow component. Comparison of traditional and 360º circular injection port is showed in Figure 3. The traditional injection port delivers the flash steam into the internal flow of compressor directly, which may produce strong disturbance on main flow channel and the non-uniform flow at the entrance of the second stage impeller. The 360° circular refrigerant injection port enhances the flow uniformity at the entrance of the second stage impeller and reduces the influence of gas turbulence on impeller efficiency.

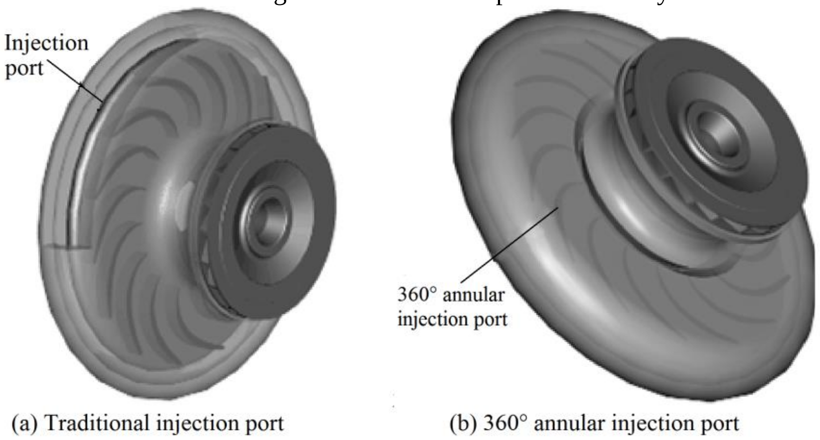
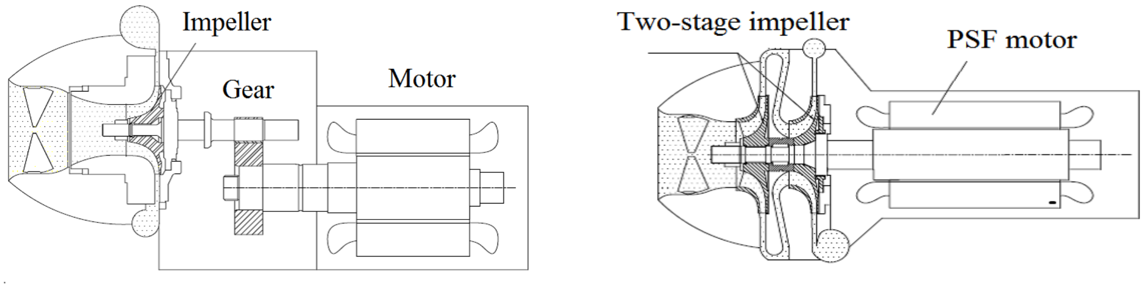


Fig.3 Comparison of traditional and 360º circular injection port

2.3. Two-stage impeller directly driven by PSF motor

Mechanical efficiency is an important factor to evaluate the centrifugal compressor performance. The traditional frequency-convertible compressor not only adopts the speed-increasing gear to meet the requirements of high pressure ratio, but also needs 4 supporting points of radial bearings due to the motor speed limitation, as shown in Figure 4 (a). The mechanical loss of the speed-increasing gear and 4 radial bearings accounts for about 4% of the power consumption under full-load condition. Under part-load condition, the mechanical loss can reach 8% of the unit power consumption. For the fixed frequency centrifugal compressor, the mechanical loss will be even larger. What’s more, the gear pair with high-speed operating moves relatively in the running process, which produce the transfer torque and a strong vibration.



(a) Traditional frequency-convertible compressor (b) PSF centrifugal compressor

Fig. 4 Structure comparison of traditional frequency-convertible compressor and PSF centrifugal compressor

PSF centrifugal compressor improves the conventional transmission mechanism based on high speed permanent-magnetic synchronous motor. The speed-increasing gear for traditional frequency-convertible compressor is removed. The single axis and 2 radial bearings are adopted to achieve power transmission and structural stability, as shown in Figure 4 (b). The improved structure has the following advantages: (1) the motion parts of centrifugal compressor are reduced and the structure is more simple and reliable; (2) the radial load of bearings and axle weight decreased greatly, the stability and reliability of the compressor is enhanced; (3) mechanical loss just occurred in 2 radial bearings, and correspondingly the mechanical efficiency of compressor is greatly improved; (4) the speed-increasing gear is removed, so the size and weight of whole unit is greatly reduced; (5) the compressor noise and vibration during operation is estimated.

2.4. High-speed PSF motor and inverter

Motor efficiency and inverter efficiency also have important influences on the performance of centrifugal compressor. Triple-phase asynchronous motor is usually used in traditional variable frequency centrifugal compressor. Under the operation of three-phase current, the motor stator generates a magnetic field which rotates at a certain speed. Rotor is derived to rotate by the electromagnetic force based on the magnetic field. Rotor speed cannot be equal to the rotation speed of the magnetic field; otherwise there is no current generated in the rotor and cannot produce electromagnetic torque. The PSF motor adopts the permanent-magnet synchronous rotor with high-speed and high-power. The permanent-magnet synchronous electrode is directly mounted on the rotor surface by a special process, which is totally different from the triple-phase asynchronous motor. In the rotating magnetic field generated by the motor stator, the permanent-magnet synchronous rotor produces its own magnetic field and interacts with the rotating magnetic field. So the permanent-magnet synchronous rotor is rotated by the rotating magnetic field synchronously with the same speed. What's more, four-quadrant controlled rectifier is used in the frequency converter.

Compared with the traditional triple-phase asynchronous motor, the permanent-magnet synchronous motor with high-speed and high-power has some remarkable advantages. Such as: the motor is manufactured with compact structure and small size than traditional motor with ordinary power, which can effectively save a lot of material; the traditional transmission mechanism is removed by directly connected with the original motivation, which has small noise and high transmission efficiency; the dynamic response time of permanent-magnet synchronous motor is shorter because of small rotor rotational inertia; the excitation system loss is eliminated and the motor efficiency is improved by using permanent-magnet synchronous motor with simple and reliable structure; the efficiency of frequency converter is up to 97% under the same power consumption condition.

3. Heat Pump District Heating System

3.1. PSF centrifugal heat pump design specifications

The system is mainly comprised of a PSF centrifugal compressor, a shell and tube condenser, a plate heat exchanger, a main electronic expansion valve, a shell and tube evaporator, a sub expansion value and water pumps. Table 1 summarizes the components of the PSF centrifugal heat pump system along with the major specifications.

Table 1 Design specifications of major components of PSF centrifugal heat pump

Components	Design specifications
Compressor	Centrifugal compressor; Volume flow rate: 1630 $m^3 \cdot h^{-1}$; Nominal rotational speed: 11000 rpm.
Condenser	Shell and tube; shell-side (R134a) ; shell diameter: Φ700 mm; tube-side (water):copper; tube diameter: Φ19.05 mm; tube number: 400; tube length: 3.5 m.
Evaporator	Shell and tube; shell-side (R134a) ; shell diameter: Φ850 mm; tube-side (water):copper; tube diameter: Φ19.05 mm; tube number: 320; tube length: 3.5 m.
Plate heat exchanger	Plate type; heat exchange area: 448m^2; nominal heat capacity: 1600 kW.
Main expansion valve	Effective flow area: 8.5e-4 m^2.
Sub Expansion valve	Effective flow area: 2.5e-4 m^2.
Water pump	Motor capacity: 37.5 kW, volume flow rate: 150 $m^3 \cdot h^{-1}$

3.2. Field test description

The PSF centrifugal heat pumps are used in the north of China for district heating. There are a lot of industrial waste heat sources, for example, chemical industry waste, oil refinery waste water and chemical fertilizer waste source. In order to evaluate the operating performance of the designed PSF centrifugal heat pumps, a field test is conducted in Lijingwan community, Shijiazhuang City, Hebei Province. According to the building project planning, the total heating demand of waste recovery heat pump project is up to 790.5 MW, which can satisfy the heating supply for civil buildings of more than 20 million square meters. Then the actual system performance, economic analysis and environment protection of PSF centrifugal heat pump is validated to recycle low grade heat source for heating.

Fig.5 Field test site of district heating using PSF centrifugal heat pumps

The building area of the tested project is 80000 square meters, and floor radiation heating is used in winter, which expected supply and return water temperature as 45 and 35℃ respectively. The heat sink of floor heating is provided by two 500RT PSF centrifugal heat pump units, both models are LSBLX1800SVP. The heat source is supplied by industrial waste heat with temperature of 25℃. Field test site of district heating system are shown in Figure 5.

3.3. Test conditions

According to the testing result of Air Conditioning Equipment Quality Supervision and Inspection Center, the actual performance of PSF centrifugal heat pump system is analyzed. The compressor power consumption is measured by a power analyser (HIOKI 3169-20/21) with an accuracy of ±(0.5% of reading +0.1% of full scale) and measurement range of 0-1000 A. The temperatures of centrifugal heat pumps are measured using Pt100 thermal resistance with an accuracy of ±0.2℃. Refrigerant pressures are measured using pressure gauge (accuracy, ±0.2% of reading) with a measuring range of 0-3 MPa. The water mass flow rate is measured by an ultrasonic flow meter (accuracy, ±1.5% of reading) with a measurement range of Φ25-Φ500 mm. All the field test data, such as temperature, pressure, water mass flow rate and electrical power are collected by a calibrated Agilent HP34970 data acquisition system. The measured data throughout a test process are collected and recorded at a time interval of 30 s.

Beside this test results, the temperature and humidity of typical rooms are also collected and recorded to evaluate the design methods and room comfort. Temperature and humidity are measured by hygrothermograph (±0.3℃, ±5%RH) and recorded with temperature and humidity measuring meter (±0.3℃, ±2%RH). The measuring range of Hygrothermograph (HM34) is from -40℃ to 85℃ for temperature and from 0%RH to 100%RH for humidity, respectively.

4. Results and discussion

4.1. Compressor efficiency

According the test standard of ARI 550/590(I-P)-2011, The PSF centrifugal compressor was evaluated experimentally to investigate the effect of these new designs. The efficiency of PSF centrifugal compressor is great improved based on the experimental results. It is can be seen from Figure 6 that the adiabatic efficiency reached to 87.6% under the most of the working conditions. Even for 25% part-load condition, the adiabatic efficiency is improved to 78.1%, which is 10.3% higher than traditional frequency-convertible centrifugal compressor.

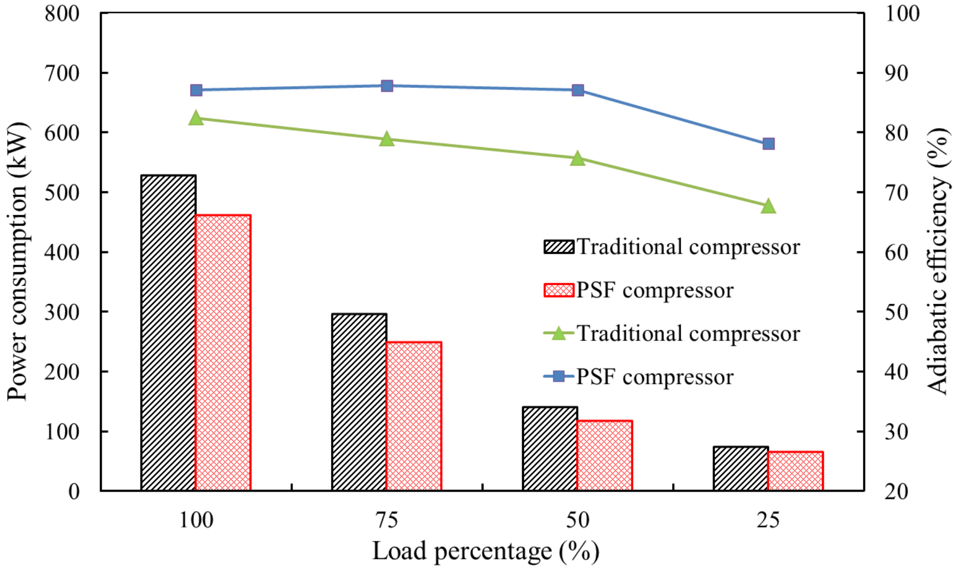


Fig. 6 The adiabatic efficiency of PSF centrifugal compressor under different load percentage

The comparison on mechanical efficiency of traditional frequency-convertible centrifugal compressor and PSF centrifugal compressor is showed in Figure 7. The mechanical efficiency of PSF centrifugal compressor is 97%-98% for all of the working conditions. The average improvement of mechanical efficiency is 3.5% when compared with traditional frequency-convertible centrifugal compressor. In other words, the new structure of two-stage impeller directly driven by PSF motor can significantly improve the mechanical efficiency for PSF centrifugal compressor.

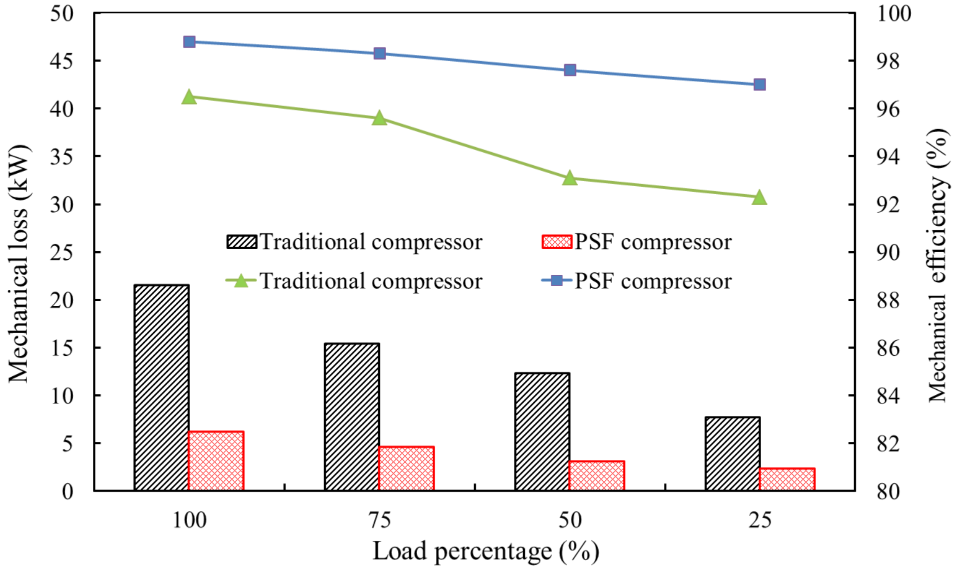


Fig. 7 The mechanical efficiency of PSF centrifugal compressor under different load percentage

By adopting the high-speed permanent-magnet synchronous motor and inverter, the motor efficiency of PSF centrifugal compressor is great improved under all the working conditions. As showed in Figure 8, the electric efficiency under full-load condition is 94.4% for traditional frequency-convertible centrifugal compressor and 97.2% for PSF centrifugal compressor, respectively. For 25% part-load condition, the electric efficiency of PSF centrifugal compressor is 90.1%, which is 4.8% higher than traditional frequency-convertible centrifugal compressor.

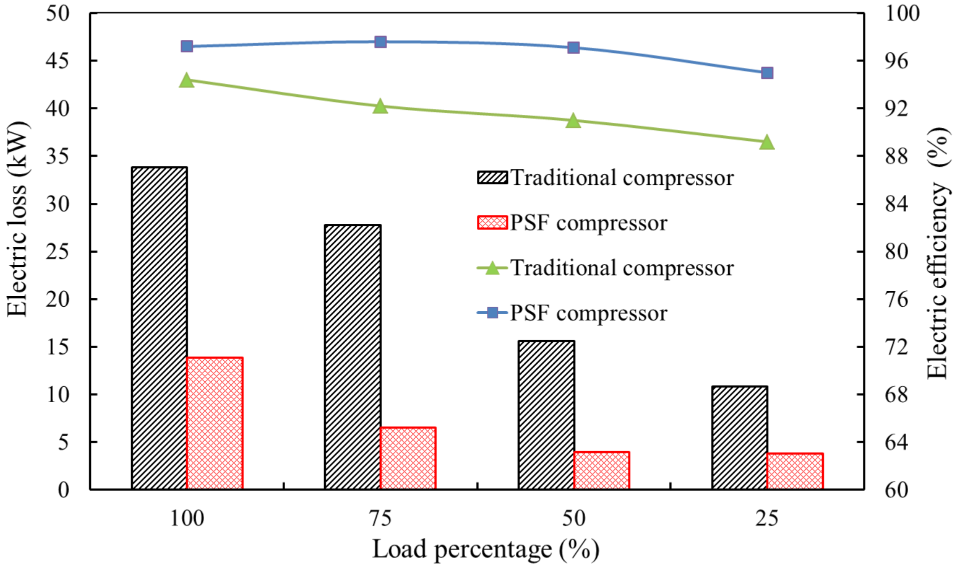


Fig. 8 The electric efficiency of PSF centrifugal compressor under different load percentage

4.2. *System performance of centrifugal heat pump*

The measured system COP curves of PSF centrifugal heat pump with 45℃ hot water supply are shown in figure 9. It can be seen that the COPs under part load conditions are much higher than 100% load condition. When the water outlet temperature of evaporator side is 10℃, the COP is 6.2 and 7.1 for 100% and 40% load condition. The maximum COP is up to 9.3 for the water outlet temperature of 20℃ under 50% load condition.

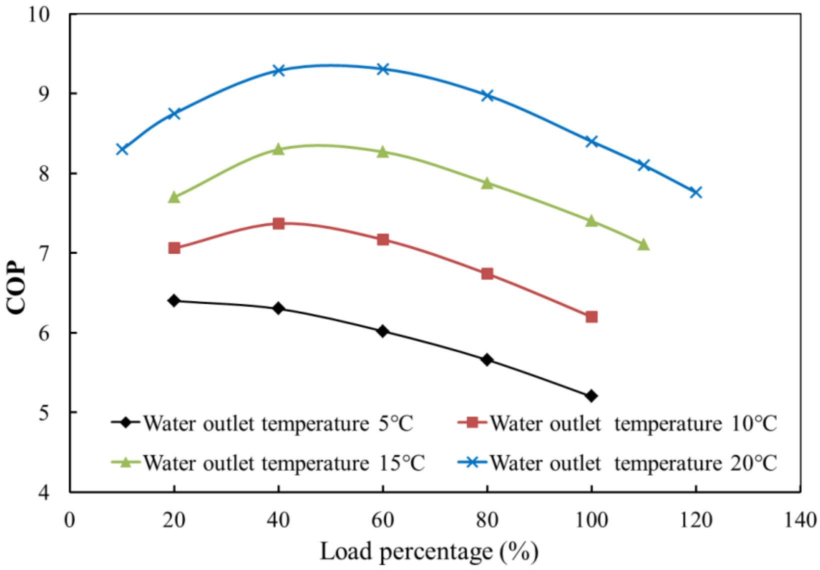


Fig. 9 The measured system COP with 45℃ hot water supply

Figure 10 presented the measured system COP curves with 50℃ hot water supply. When the water outlet temperature is 10℃, the system COPs are 5.4 and 6.5 for 100% load condition and 40% load condition, respectively. It is concluded the PSF centrifugal heat pump has excellent system performance under partial load.

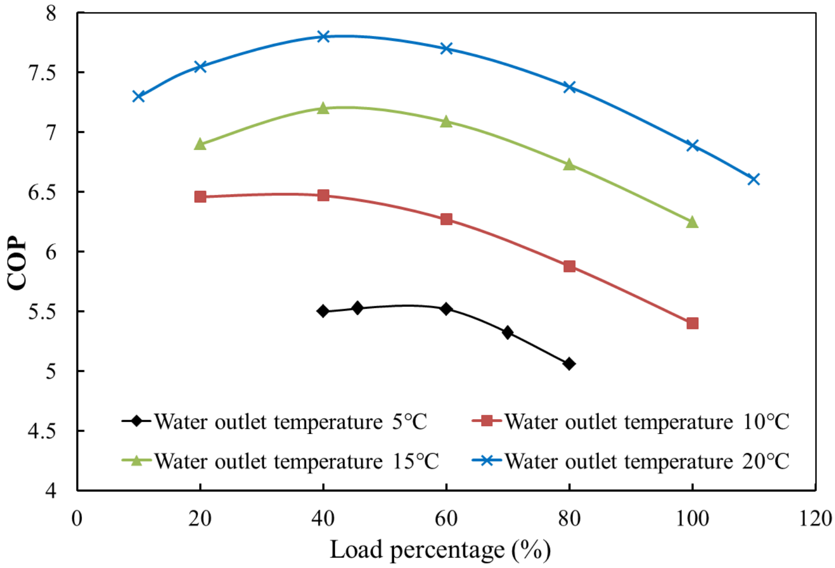


Fig. 10 The measured system COP with 50℃ hot water supply

With the above measured data, as for 500RT Permanent-magnetic Synchronous Frequency-convertible heat pump units, when the water inlet and outlet temperatures in the evaporator side are 15 and 10℃ respectively and the water temperatures of the condenser inlet and outlet are 35 and 45℃ respectively, the COP can reach 6.2. And when the water temperatures of the condenser inlet and outlet are 40 and 50℃ respectively, the COP can reach 5.4. The PSF centrifugal heat pump has much better performances in comparison with the traditional single-stage frequency-convertible centrifugal heat pump. Table 2 shows the comparison between two products with a capacity about 500RT.

Table 2 Comparison of traditional frequency-convertible and PSF centrifugal heat pump

Temperature of inlet water in the condenser/℃	Temperature of outlet water in the condenser/℃	Traditional single-stage frequency-convertible			Permanent-magnetic Synchronous Frequency-convertible		
		Heating capacity /kW	Input power /kW	Heating COP	Heating capacity /kW	Input power /kW	Heating COP
35.0	45.0	1740.2	347.3	5.0	1759.5	286.8	6.2
40.0	50.0	1589.6	361.1	4.4	1612.3	298.5	5.4

5. Conclusions

The PSF centrifugal compressor adopted some key technologies such as large working range 3-Dimentional impeller, 360° circular refrigerant injection port, two-stage impeller directly driven by high-speed PSF motor and high-speed inverter. The detail information of these technologies is introduced to show the advantage of efficiency improvement. The compressor efficiency and system COP are greatly improved relative to traditional single-stage frequency-convertible centrifugal heat pump.

Experimental results show that the adiabatic efficiency reached to 87.6% under the most of the working conditions. Even for 25% part-load condition, the adiabatic efficiency is improved to 78.1%, which is 10.3% higher than traditional frequency-convertible centrifugal compressor. The mechanical efficiency of PSF centrifugal compressor is 97%-98% for all of the working conditions. The average improvement of mechanical efficiency is 3.5% when compared with traditional frequency-convertible centrifugal compressor. The motor efficiency of PSF compressor is 95%~97.6% under the most of the working conditions.

In the practical application of district heating project, the PSF centrifugal heat pump with low grade industrial waste heat recovery and heating supply has obvious advantages. The heating COP of 500 RT centrifugal heat pump units is up to 6.2 with the water outlet temperature of 10℃ in evaporator side under full load condition. As a new high-efficient, energy saving and clean heating method, PSF centrifugal heat pump with industrial waste heat recovery has a promising prospect in district heating application.

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